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## Characterization of Lasers for Use in Analog Photonic Links

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## **CHARACTERIZATION OF LASERS FOR USE IN ANALOG PHOTONIC LINKS**

### **EXECUTIVE SUMMARY**

- Laser characterization metrics are described.
- The procedure for measuring laser noise spectrum is presented.
- The procedure for measuring laser linewidth is presented.
- The procedure for measuring laser optical spectrum is presented.
- The measured laser noise spectrum of all lasers is shown.
- The measured linewidth of all lasers is shown.
- The measured laser optical spectrum of all lasers is shown.



# CHARACTERIZATION OF LASERS FOR USE IN ANALOG PHOTONIC LINKS

## 1 INTRODUCTION

A survey of seven lasers that reside in Section 5652 was conducted to characterize their performance as it relates to analog photonic link applications. These single-frequency lasers comprise a variety of different architectures, output power levels, and form factors. It is these trade spaces that will become important when making a final decision regarding the selection of a laser for a particular need.

Diode-pumped solid-state (DPSS) lasers produce very narrow linewidths along with high output powers and a low relative intensity noise (RIN) spectrum. However, they are often bulky, specifically in single-longitudinal mode models, and sensitive to environmental factors due to their free-space optical design. Er-doped fiber lasers are capable of modest to high powers and very narrow linewidths but suffer from larger package sizes similar to DPSS systems. Small form factor lasers such as distributed feedback (DFB) semiconductor lasers and external cavity diode lasers (ECDLs) can exhibit modest output powers but at the expense of increased linewidth. Narrow linewidth semiconductor lasers have been produced but with output powers that are too low for high performance radio frequency (RF) photonic link applications.

Ideally, lasers for use in analog photonic links would be high-power ( $>100$  mW), have a shot-noise-limited (SNL) RIN spectrum, ultra-narrow linewidth ( $<1$  kHz), and be contained in a rugged, small form factor package ( $\sim 2.5$  cm $^3$ ) such as a 14-pin butterfly package. Currently, no such laser can meet all of these targets at once. Therefore, photonic link designers must decide on which factors are most important in achieving their design goals. The target of this report is to aid in that decision making process by presenting the results of careful measurements taken related to the most important laser parameters.

Section 2 will define the three main metrics used in characterizing a lasers' optical performance in regard to analog photonic links, specifically linewidth, RIN, and optical spectrum. A discussion of the methodology used in measuring each of these properties is contained in Section 3. Measurements of the RIN spectrum, linewidth, and optical spectrum are presented in graphic form along with a discussion of the results occurs in Sections 4 - 6. Finally, in Section 7, a summary and conclusion are given.

## 2 LASER CHARACTERIZATION METRICS

Noise generated by the laser can have a significant impact on the performance of a photonic link when it occurs with high intensity at radio and microwave frequencies such as decreased sensitivity and dynamic range. Therefore, great care must be taken to accurately measure the noise spectrum and identify the frequencies that have a high power spectral density at specific regions of interest when considering a laser for use in a photonic link. The most common sources of laser intensity noise are the result of instabilities in the output power due to several factors such as relaxation oscillations and from multiple longitudinal modes competing for the same gain. Another source of laser intensity noise can actually be the result of phase noise that is converted to intensity noise. A source of this type of conversion can be from double Rayleigh scattering which causes incoherent interference between time-delayed copies and the original signal. This is referred to as multipath interference which results in an intensity fluctuation as detected by a photodiode.

The RIN of a laser is defined as the output noise power spectral density, in a 1 Hz bandwidth, normalized to the average output power [1]. From DC to the kHz frequency range, most of the intensity is due to technical sources such as the vibration of cavity mirrors and temperature variations inside the laser. In DPSS and Er-doped fiber lasers, relaxation oscillations dominate the kHz frequencies due to the fact that their upper-state lifetime is longer than the cavity dampening time [2]. However, semiconductor lasers like DFBs and ECDLs have their relaxation oscillations occurring in the GHz range. The GHz frequency range

can also be affected by the presence of additional longitudinal modes from all four laser architectures and their spacing is a function of cavity length.

While the laser RIN remains constant with increasing detector photocurrent, the shot noise limit decreases. Therefore, the measurement should be made with the maximum amount of incident power that the photodiode can safely handle in order to provide the dynamic range necessary to accurately measure the laser RIN. The shot noise limit is given by the following equation in linear form:

$$RIN_{SNL} = 2e/I_{dc} \quad (1)$$

where  $e$  is magnitude of the charge of an electron ( $1.60 \times 10^{-19}$  C) and  $I_{dc}$  is the average photocurrent measured by the photodiode. To convert this result into the logarithmic form, simply take the log and multiply it by 10. As an example: if the DC photocurrent measured by the photodiode is 10 mA, the SNL RIN would be -165 dBc/Hz across all frequencies.

The linewidth of a laser is generally driven by the amount of phase noise present. The theoretical limit of which is determined by the randomness of the phase of spontaneously emitted radiation. Spontaneous emission is a homogeneous broadening process that results in a Lorentzian lineshape [3]. In practice, phase noise results from temperature variations which give rise to a change in the refractive index of the gain medium and from mechanical vibrations that disturb the laser cavity. The net result of all of these factors is a laser with a finite linewidth that can also vary rapidly in frequency.

When reporting the measured linewidth of a laser, is important to also include the observation time used to make the measurement. In addition to the natural linewidth, the frequency drift of the laser will cause an artificial broadening of the measured linewidth spectrum. While sampling over a longer time period provides a more practical measure of the effective linewidth of a laser it should not be confused with the potentially much narrower intrinsic linewidth. The linewidth spectrum often appears to have a Gaussian peak with Lorentzian wings which is the result of a natural Lorentzian lineshape that is rapidly varying in frequency.

The optical spectrum of a laser to be used in an analog photonic link would ideally consist of a single infinitely narrow peak indicating single-frequency operation. However, in the real world this is not the case. The relatively large emission bandwidth of most lasing materials coupled with the laser cavity's ability to support many longitudinal modes results in an output spectrum containing several peaks. This fact challenges laser manufacturers to eliminate these additional axial modes in order to produce the desired single-frequency operation. If the additional axial modes are not sufficiently suppressed, they may appear in the RF spectrum which could be problematic for some applications.

In order to produce single-frequency operation, laser vendors can employ a number of approaches to make the cavity frequency-selective. One type of laser characterized in this report, semiconductor DFBs, employ a distributed reflective structure inside the gain medium to promote single frequency operation. Er-doped fiber lasers can employ two different techniques to select a single longitudinal mode. One is to use a fiber Bragg grating (FBG) on either end of the doped section and the other is to produce a "virtual ring" structure [4] by placing wave plates surrounding the gain element but inside the fiber Bragg gratings. ECDLs can employ either a FBG or a planar Bragg grating (PBG) to achieve single frequency operation [5]. The final type of laser characterized in this report, DPSS lasers, can utilize a unidirectional ring design, intra-cavity etalon, or use wave plates to create a twisted-mode resonator, all producing the sought after frequency selectivity.

Output power is another importance measure of a laser's performance. In particular, intensity-modulated direct-detection links benefit from increased photocurrent made available by higher power optical sources. The benefits of increased photocurrent are higher RF gain, compression dynamic range, and spurious-free dynamic range while lowering the RF noise figure [6].

Due to their increased size and the ability to dope bulk solid-state laser crystals at a higher level, DPSS lasers are capable of producing the most output power of the three types of lasers contained in this report.

Fiber lasers on the other hand have to be doped at much lower concentrations and therefore can only create higher powers with longer lengths of fiber which increases their overall size. An exception is when phosphate glass fibers are co-doped with Yb and Er in an attempt to shorten the length needed to achieve a particular amount of gain. The lowest power, but most compact, lasers of the group are the semiconductor DFB and ECDL lasers. These lasers either produce high power or narrow linewidth but not both in the same device.

### 3 MEASUREMENT METHODOLOGY

The methodology used to measure the RIN of each laser will be presented in this section of the report. There are a couple subtleties that prevent this measurement from being straightforward. The first subtlety is the fact that the noise of the lasers will typically be below the noise floor of the electrical spectrum analyzer (ESA) used to make the measurement. Therefore, an RF amplifier will be needed to raise the laser noise signal to an acceptable level. The second subtlety comes from the aforementioned amplification process which adds additional noise to the intended signal being measured. Because of this fact the amplifier gain and noise figure have to be characterized separately so that they can be accounted for later on in the process.

All lasers tested were set at the maximum power level with which single-frequency operation was achieved. By way of a variable optical attenuator (VOA) the output of each laser was reduced to a level that resulted in a photocurrent of 10 mA produced by the measurement photodiode. First, the gain from the RF amplifier, which is used to elevate the laser noise signal to a measurable level, will need to be measured with a network analyzer and then subtracted from the measured total noise [7].

In order to cover the wide bandwidth (10 kHz to 40 GHz) of this measurement, three different photodiode/RF amplifier combinations were needed. A DCS50S photodiode from Discovery Semiconductors, Inc. along with a Sonoma Instruments Model 310 amplifier were used to cover the RIN spectrum from 10 kHz to 1 GHz. The 1 GHz to 20 GHz range was measured using a DCS30S from Discovery Semiconductors, Inc. and AML Communications' 0618L2403 amplifier. Also from Discovery Semiconductors, Inc., the DSC10H was used for the highest frequency band (20 to 40 GHz) along with a MITEQ AMF-6F-20004000-40-8P amplifier.

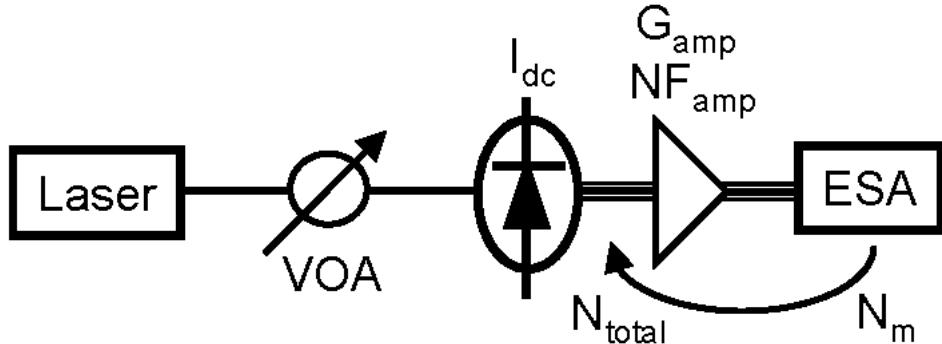


Fig. 1. The experimental setup used to measure the RIN of each laser [7]. The (VOA) is used to reduce the laser's output to a level that produces 10 mA of photocurrent ( $I_{dc}$ ) at the photodiode. The signal from the photodiode is then amplified and displayed on the ESA. The gain ( $G_{amp}$ ) and noise figure ( $NF_{amp}$ ) of the amplifier must be measured independently of the laser's RIN and manually subtracted later in order to realize the true laser intensity noise spectrum.

The linewidth of each laser was measured using the delayed self-heterodyne (DSH) technique. Due to the large time delays that are made possible with optical fibers, a laser can be incoherently interfered with itself to produce a beat tone that is broadened by the effective linewidth of the laser over some finite time period [8]. The amount of optical delay provided by the fiber dictates the minimum linewidth that can be measured with this technique. A delay of 186  $\mu$ s was achieved by way of a 37.5 km spool of dispersion-compensated single-mode fiber in the linewidth setup used for this series of measurements. This delay results in a minimum, incoherently combined, linewidth of 5.38 kHz that can be measured by the system from a single pass through the delay loop. Multiple passes (up to 4) were achieved resulting in a minimum linewidth resolution of approximately 1.34 kHz. However, with each pass through the delay loop, the signal-to-noise ratio degrades due to a finite loss in the optical fiber. Also, longer fiber lengths required to achieve higher resolution make them more susceptible to environmental influences such as temperature and acoustic pickup that artificially broaden the laser's measured linewidth. In addition, the 1/f, or flicker noise, broadens the self-heterodyne lineshape when long delays are present [9]. For lasers with ultra-narrow linewidths ( $\sim$ 1 kHz) this setup will overestimate the linewidth due to partially coherent interference. The overestimation could be as large as a factor of 2 or 3 if only one pass through the interferometer is used [10].

The mixing of the two electric fields yields a self-convoluted spectrum displayed on the ESA that is double the width of the original laser signal. Because lasers generally display frequency jitter and 1/f noise a full-width at half-maximum (FWHM) linewidth determination is not sufficient. Instead, it is prudent to first fit the measured spectrum with a Lorentzian lineshape and use the 20 dB bandwidth to determine the FWHM linewidth. These low frequency noise sources will tend to cause the measured FWHM linewidth to increase with longer fiber delays [8] which justifies deducing the 3 dB linewidth from the 20 dB Lorentzian fit value.

For this experiment a setup like the one illustrated below in Figure 2 was used. The 50/50 splitter and the 37.5 km spool of dispersion compensated single-mode fiber were both placed inside of a specially designed wooden box that was lined with Sorbothane® in order to dampen temperature changes and mechanical vibrations from the neighboring environment. The 37.5 km length of fiber was actually made up from alternating 3.125 km lengths of positive and negative dispersion fiber that were spliced together. The net effect was nearly zero total chromatic dispersion through the device as well as reduced stimulated-Brillouin scattering [11].

The resulting measured spectrum from the ESA was post-processed by way of a least squares fitting program. This program fits a Lorentzian lineshape to the laser field spectrum and returns the FWHM linewidth. The resulting spectrum and calculated linewidth for each laser can be seen below in Section 5.

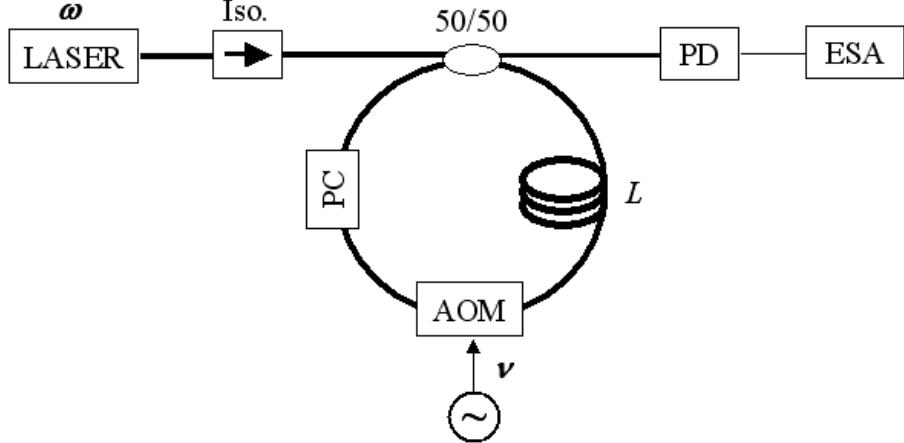


Fig. 2. The experimental setup for the DSH linewidth measurement. All 7 lasers were fed through the optical isolator (Iso.) before the power was divided equally by the 50/50 splitter. Half of the light traversed a 37.5 km length of dispersion-compensated optical fiber while undergoing a frequency shift ( $v$ ) caused by the acousto-optic modulator (AOM). The time-delayed portion of the beam was incoherently interfered with the original beam on the photodiode (PD) after recombining through the 50/50 coupler. The polarization controller (PC) was used to align the polarization of the combined electric fields and to maximize the signal on the electrical spectrum analyzer (ESA).

While the RIN spectrum provides more dynamic range and a DSH linewidth measurement offers much greater resolution, it is still instructive to measure the optical spectrum of a laser with an optical spectrum analyzer (OSA). This measurement can help to verify that spikes in the RIN spectrum are actually the result of additional longitudinal modes. Along with increased bandwidth it can also help in quantifying the side-mode suppression ratio (SMSR) and center wavelength of the laser's optical output.

The OSA used for measuring the power versus wavelength of each laser was a model AQ6319 from Ando. This unit is a diffraction grating-based OSA providing 10 pm resolution and 70 dB of dynamic range. The highest resolution is achieved when using a single-mode 9  $\mu\text{m}$ -core fiber which is the fiber type that all of the lasers tested were supplied with. Each laser was set to its maximum output power when the spectral measurement was made. With a maximum permissible input power of +25 dBm for the OSA, the use of a VOA was not needed.

## 4 LASER NOISE SPECTRA

Seven different lasers were characterized using the experimental methods outlined in the previous section. In this section, the measured RIN spectrum of each laser is presented and discussed along with some additional information related to the laser's technology, power level, and form factor.

Thorlabs now markets a single-frequency ECDL from Covega that is housed in a 14-pin butterfly package [12]. The model number of the unit tested was SFL-1550P (S/N SFL-8321). This laser was operated at a forward-bias current of 290 mA resulting in an output power of approximately 37 mW. The variable optical attenuator shown above in Figure 1 was used to reduce the incident power on the photodiode to a level which produced 10 mA of photocurrent. At the factory recommended drive current of 300 mA, the laser produced slightly more power but failed to retain single-frequency operation. This fact was noted in the manufacturer's data sheet however could prove to be problematic in many RF applications.

As seen below in Figure 3, significant peaks occur in the GHz frequency range as the result of additional longitudinal modes that are lasing. Also of note, a relaxation oscillation peak occurs around 2.5 GHz.

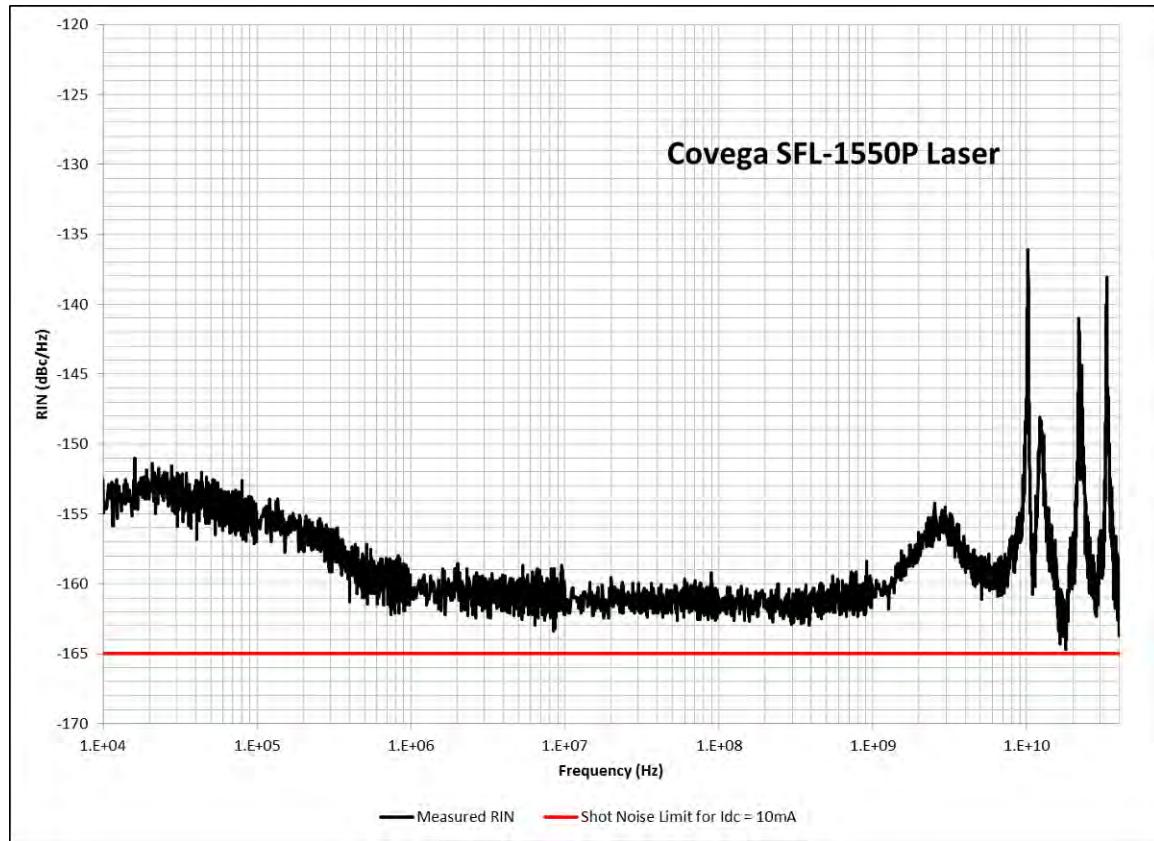


Fig. 3. The measured RIN spectrum (black) for a Covega SFL-1550P (Serial No. SFL-8321) ECDL. The laser's output power was 37 mW at 1550 nm and the DC photocurrent was 10 mA resulting in a shot noise floor of -165 dBc/Hz (red). This RIN plot shows a relaxation oscillation peak around 2.5 GHz and some larger peaks resulting from additional longitudinal modes in the 10 – 40 GHz range. The peaks at ~11, 22, and 33 GHz are the result of the ~11 GHz longitudinal mode spacing which can clearly be seen in the OSA scan (Figure 16). The peak near 12.5 GHz is likely from the mixing of the relaxation oscillation peak and the second longitudinal mode.

EM4 supplies a compact, integrated single-frequency DFB laser module named the EM600 (S/N E0037572 tested). The EM600 contains both the laser and the necessary drive electronics in one compact package that only requires a 5V DC input to operate which satisfies their technical goal of reduced size, weight, and power consumption (SWaP) [13]. At the factory settings this laser produced 80 mW and the corresponding RIN plot as seen below in Figure 4.

The EM600 has a SNL RIN spectrum throughout the entire MHz frequency range but shows a large intensity spike in the GHz range due to the relaxation oscillation frequency of the laser cavity. This type of RIN spectrum, coupled with its small form factor, make it a viable option for medium (300 kHz – 3 MHz), high (3 MHz – 30 MHz), and very high frequency (30 MHz – 300 MHz) applications. However, microwave frequency applications would be largely affected by the relaxation oscillation peak as well as the longitudinal mode spacing of 43.3 GHz which can be partially seen in the RIN spectrum below and can easily be seen in the optical spectrum in Figure 17.

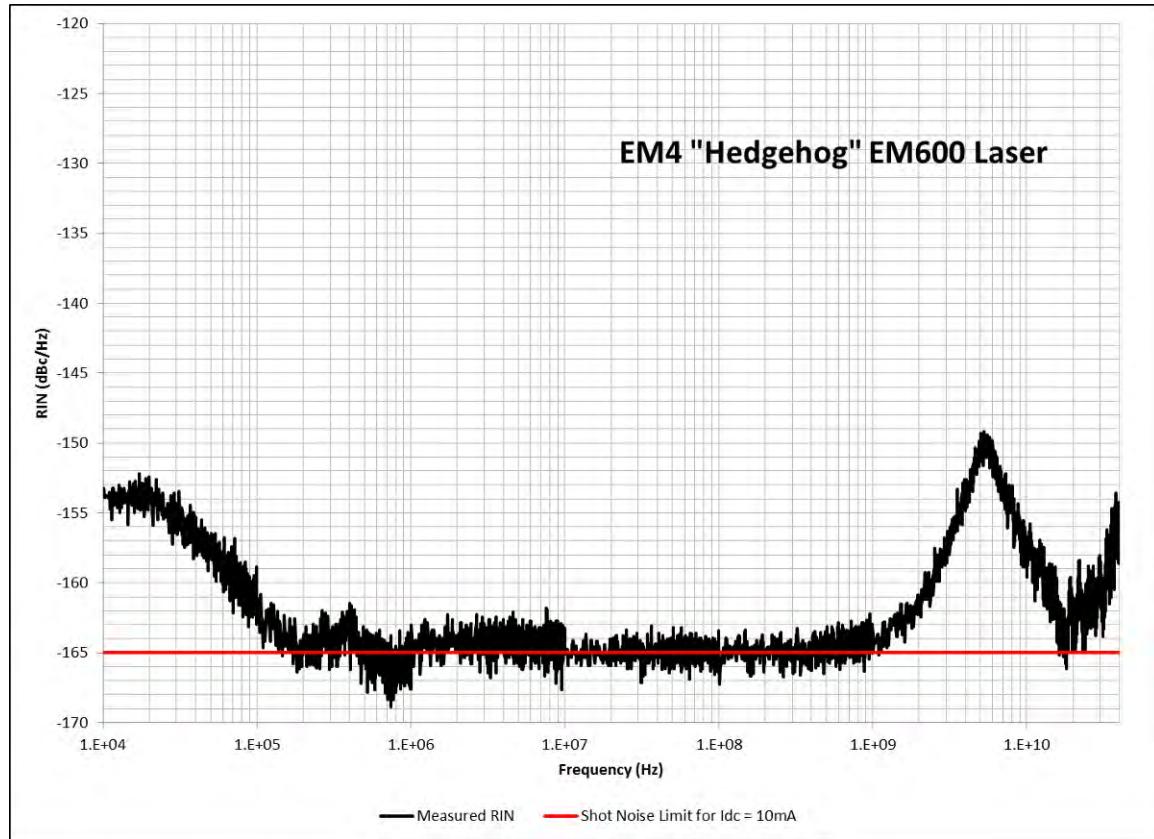


Fig. 4. The measured RIN spectrum (black) for an EM4 “Hedgehog” E600 (Serial No. E0037572) DFB laser. The laser’s output power was 80 mW at 1550 nm and the DC photocurrent was 10 mA resulting in a shot noise floor of -165 dBc/Hz (red). This RIN plot shows a relaxation oscillation peak around 5.5 GHz and another large peak is partially visible that is located above 40 GHz. The peak above 40 GHz originates from another longitudinal mode. As can be seen below in Figure 17, this laser has a longitudinal mode spacing of 43.4 GHz. This laser is SNL in the frequency range of 200 kHz – 1 GHz.

JDS Uniphase offered a single-frequency DFB laser in a telecom standard 14-pin butterfly package. The model CQF935/908 series laser (S/N 804166 tested) is rated at approximately 40 mW of output power with a drive current of 250 mA and a chip temperature of 20 – 35 °C. The characterization of this laser was conducted with the slightly higher drive current of 302 mA at a chip temperature of 25 °C resulting in an output power of 61 mW.

From the measured RIN spectrum below in Figure 5, no clear relaxation oscillation peak can be seen. The spectrum is essentially flat and ~ 10 dB above the shot-noise floor from 10 kHz – 100 MHz while falling to the shot-noise floor from 100 MHz to approximately 10 GHz. Due to the longitudinal mode spacing of 43.6 GHz, a peak can be seen to some extent at the high end of the frequency spectrum near 40 GHz.

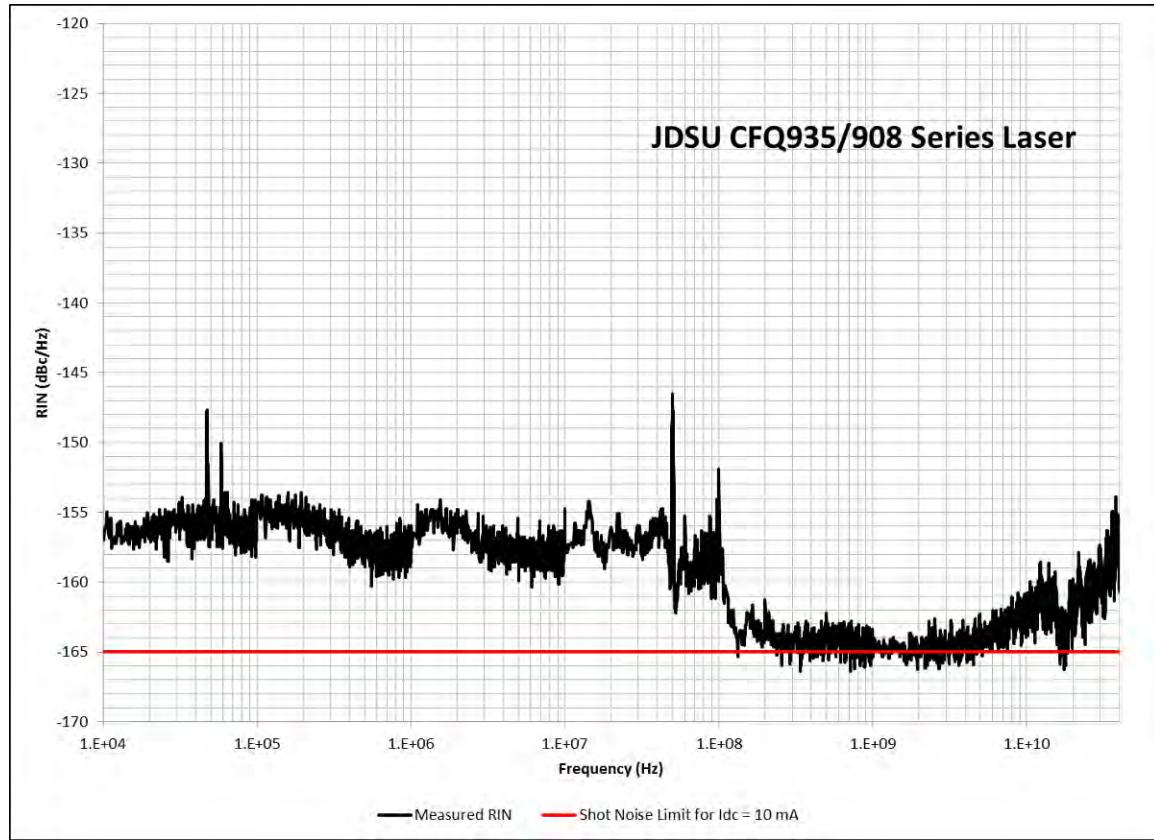


Fig. 5. The measured RIN spectrum (black) for a JDSU CFQ935/908 Series (Serial No. 804166) DFB laser. The laser's output power was 61 mW at 1550 nm and the DC photocurrent was 10 mA resulting in a shot-noise floor of -165 dBc/Hz (red). This RIN plot shows that this laser is generally no worse than 10 dB above the shot-noise floor over the entire measured frequency range of 10 kHz – 40 GHz. It's difficult to identify the presence of the relaxation oscillation peak but the part of the peak due to the second longitudinal mode can be seen out near 40 GHz. The longitudinal mode spacing for this laser is 43.6 GHz as can be seen below in the OSA scan (Figure 18). There are several narrow-band peaks throughout the spectrum stemming from undetermined sources.

As a baseline reference for low amplitude noise, a Nd:YAG DPSS laser from Lightwave Electronics (S/N 408 tested) was characterized. It should be noted that the design of this laser is from JDSU. This laser utilizes a nonplanar ring oscillator that forms a traveling wave inside the cavity [14]. This architecture avoids the problem of spatial hole burning and ensures single-frequency operation while delivering 200 mW of output power.

From 10 MHz to 40 GHz the RIN spectrum is essentially SNL. Unfortunately, this type of laser is relatively bulky and may not be suitable for some applications. In addition, the lasing wavelength of 1319 nm limits its applications due to the fact that it falls outside of the gain bandwidth of erbium-doped fiber amplifiers [7].

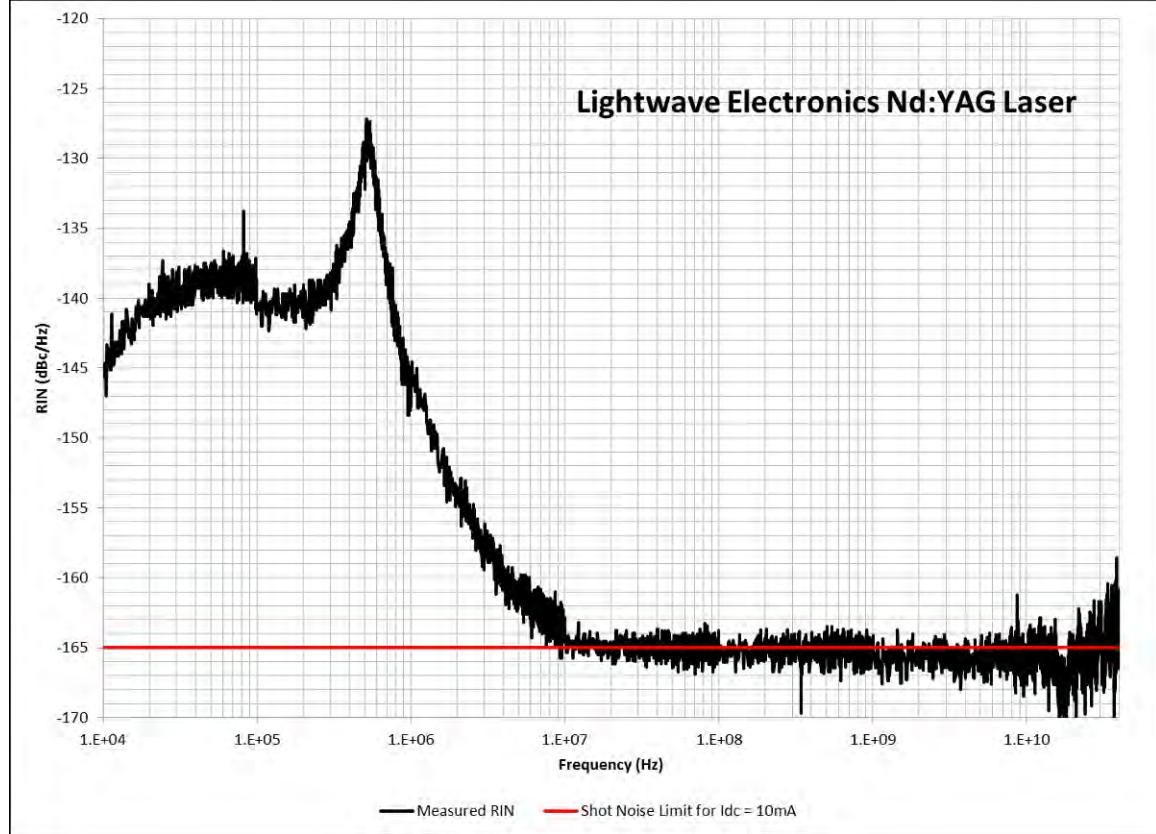


Fig. 6. The measured RIN spectrum (black) for a Lightwave Electronics (Serial No. 408) Nd:YAG laser. The laser's output power was 200 mW at 1319 nm and the DC photocurrent was 10 mA resulting in a shot noise floor of -165 dBc/Hz (red). This RIN plot shows a relaxation oscillation peak around 500 kHz and SNL performance in the frequency range of 10 MHz – 40 GHz.

NP Photonics has developed an Er-doped fiber laser named the “Rock”. They utilize phosphate glass fibers in order to increase the erbium concentration therefore achieving higher gain in a shorter length which results in a more compact device [15]. This laser system is accompanied by a separate control module that utilizes factory settings for both the temperature and drive current of the laser. The output power of this unit was nominally rated at 25 mW, however only 18.6 mW was measured.

The RIN spectrum of the “Rock” is very similar to that of the Nd:YAG system mentioned previously with the exception of the narrow peaks at 2.6 and 10.9 GHz (Figure 7). The first peak is likely the result of a second longitudinal mode that is lasing but is undetected in the optical spectrum due to a limit in the OSA’s resolution (see Figure 20). It’s unknown where the 10.9 GHz peak originates. Aside from the peaks at 2.6 and 10.9 GHz, the rest of the spectrum is SNL out to 40 GHz.

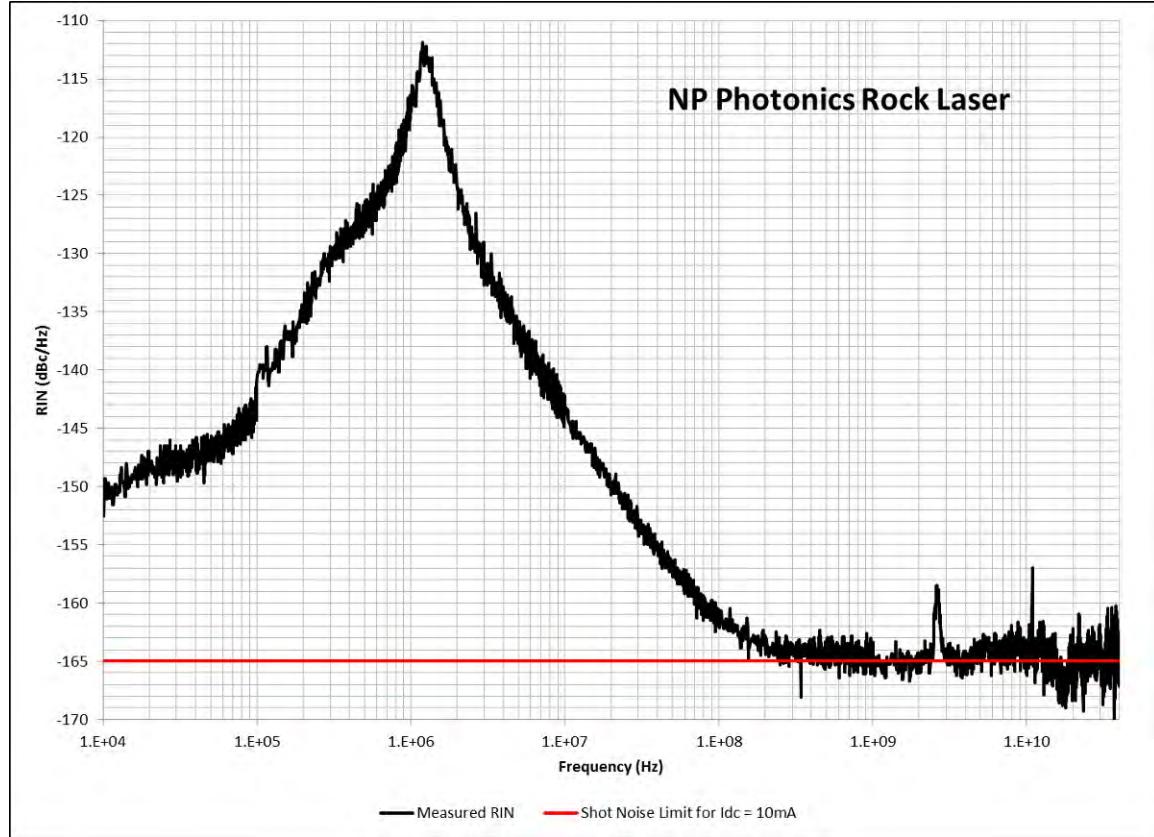


Fig. 7. The measured RIN spectrum (black) for an NP Photonics “Rock”  $\text{Er}^{3+}$  fiber laser. The laser’s output power was 18.6 mW at 1550 nm and the DC photocurrent was 10 mA resulting in a shot-noise floor of -165 dBc/Hz (red). This RIN plot shows that the laser has a very broad relaxation oscillation peak around 1 MHz. The laser is essentially SNL from 200 MHz – 40 GHz except for the narrow peaks at 2.6 and 10.9 GHz. This peak at 2.6 GHz could be from a second longitudinal mode which would be spaced approximately 20 pm from the main peak in the optical spectrum. This peak may be present but unresolved in the optical spectrum seen in Figure 20. The source of the 10.9 GHz peak is unknown.

The Ethernal laser from Orbita Lightwave (S/N 1071 tested) is an Er-doped fiber laser that employs a couple of unique technologies to produce single-frequency operation combined with high output power and low noise. First, they use a patented “slow light” laser oscillator that increases the cavity photon lifetime which reduces both intensity and phase noise. Second, they developed a linear “virtual ring” cavity that is frequency selective and produces a traveling wave which eliminates spatial hole burning [4].

The measured output power of the laser tested was 85 mW however the vendor offers this same model with up to 350 mW of output power. The laser head has the capability with its own on-board electronics to run with just a 6V DC supply albeit at a reduced level of noise performance. With some additional external electronics the noise performance can be significantly increased. The RIN spectrum shown below in Figure 8 is from an Ethernal laser that did not benefit from the additional noise reduction circuitry.

Similar to the “Rock” and Nd:YAG laser, the Ethernal’s RIN spectrum displays a large relaxation oscillation peak in the MHz range while the GHz frequency range is SNL. Also like the “Rock” laser, there is a small peak in the GHz range that results from the presence of a second longitudinal mode that is lasing. At a frequency of 1 GHz, this peak would occur too close to the main peak to be resolved by the OSA, thus its absence from the optical spectrum seen below in Figure 21.

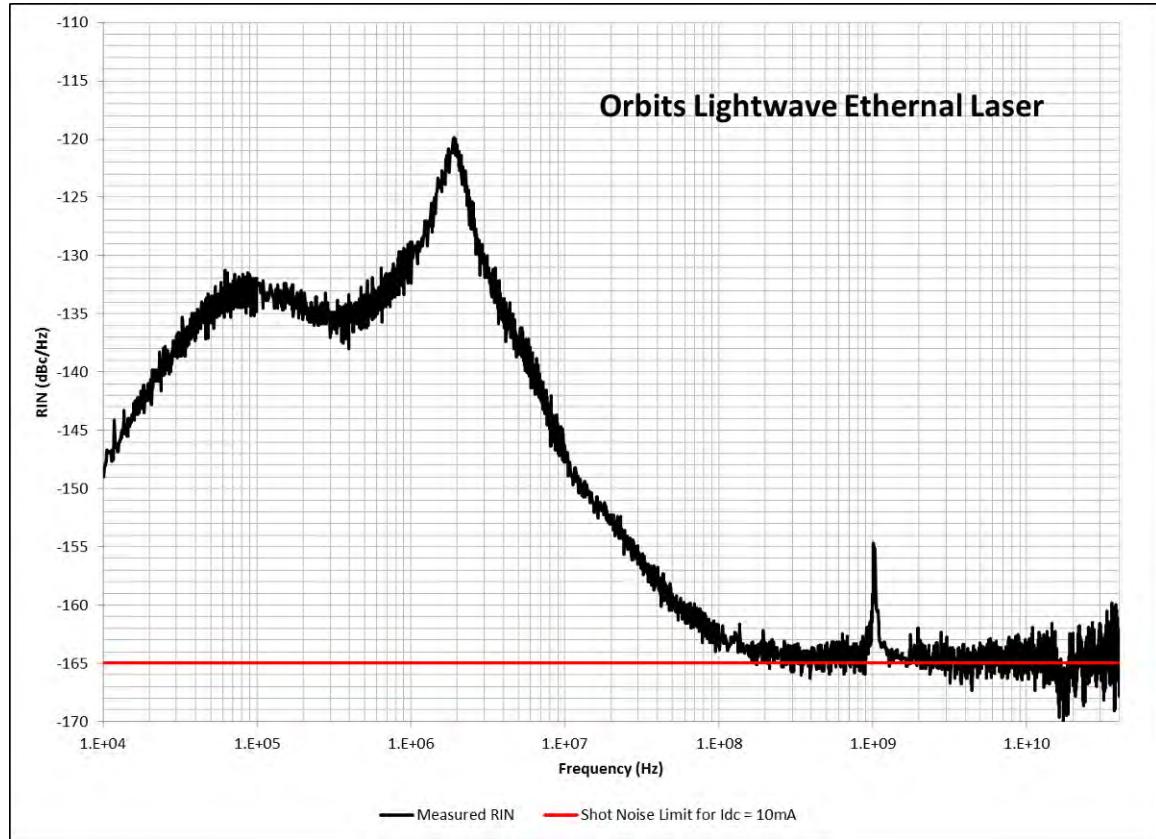


Fig. 8. The measured RIN spectrum (black) for an Orbita Lightwave “Ethernal”  $\text{Er}^{3+}$  fiber laser. The laser’s output power was 85 mW at 1550 nm and the DC photocurrent was 10 mA resulting in a shot noise floor of -165 dBc/Hz (red). This RIN plot shows that the laser has a very broad relaxation oscillation peak around 2 MHz. The laser is essentially SNL from 200 MHz – 40 GHz except for the peak around 1 GHz. This peak at 1 GHz could be from a second longitudinal mode which would be spaced approximately 8 pm from the main peak in the optical spectrum. Since the OSA only has a resolution of 10 pm, this peak may be present but unresolved in the scan seen below in Figure 21.

The Planex laser (S/N 100629 tested) from Redfern Integrated Optics (RIO) is a semiconductor ECDL with a PBG that produces single-frequency output in a Telecordia-qualified 14-pin butterfly package [5]. RIO's PBG technology offers narrow linewidth and lower frequency noise than similarly package DFBs while also providing better vibration performance as compared to FBG-based ECDLs [5]. Although the package size is attractive, the output power produced by this laser is relatively low. At a drive current of 140 mA the Planex laser provides 15.9 mW of optical power.

Like DFB lasers the kHz and MHz frequency ranges of the Planex's RIN spectrum (Figure 9) are fairly close to the shot-noise floor. However, this laser has several peaks occurring in the GHz range especially above 10 GHz. The relaxation oscillation peak occurs at 8.8 GHz with the other peaks resulting from additional longitudinal modes.

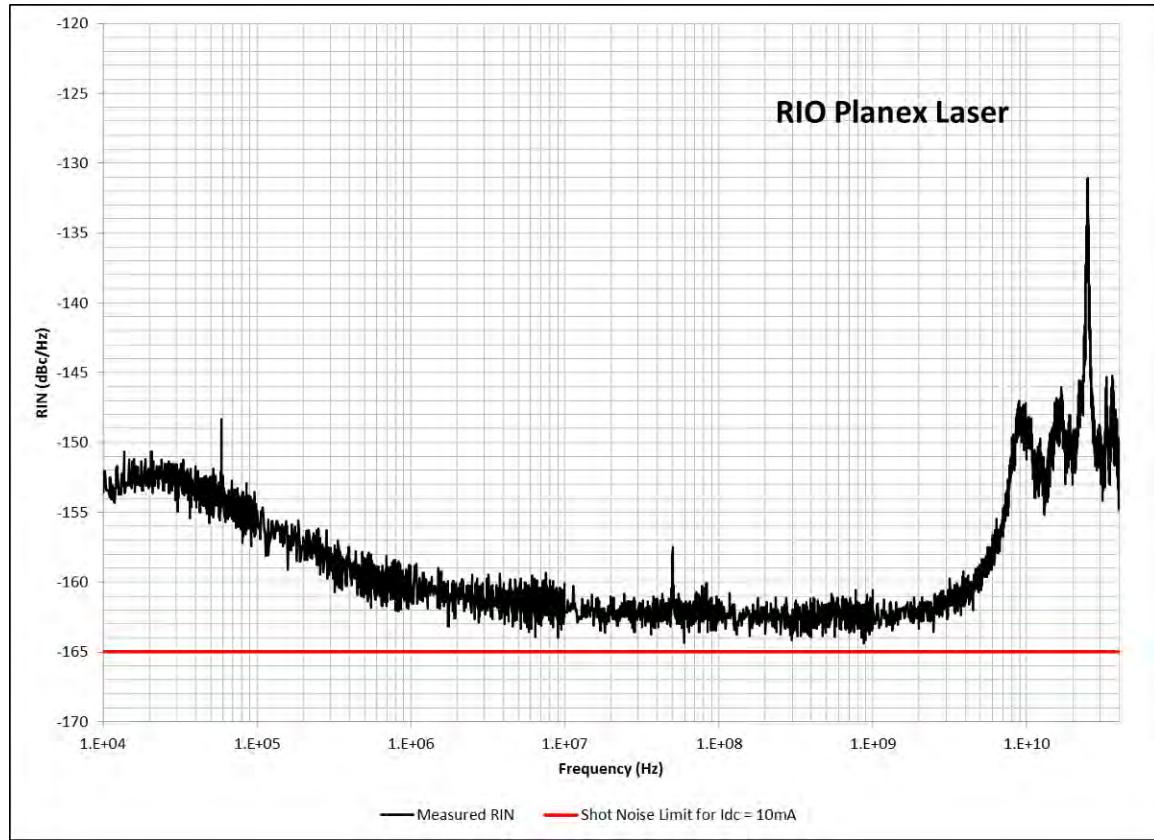


Fig. 9. The measured RIN spectrum (black) for a RIO Planex ECDL. The laser's output power was 15.9 mW at 1550 nm and the DC photocurrent was 10 mA resulting in a shot noise floor of -165 dBc/Hz (red). However, there are several large peaks in the range from 2 – 40 GHz. The relaxation oscillation peak occurs at 8.8 GHz with the other peaks resulting from additional longitudinal modes (Figure 22).

## 5 LASER LINENWIDTH SPECTRA

In this section, the measured linewidth and DSH spectrum of each laser are presented in graphical form. As previously discussed in section 3, the DSH technique was employed to make this measurement. Also previously stated, the linewidth setup used will overestimate the linewidth due to partially coherent interference for lasers with ultra-narrow linewidths ( $\sim 1$  kHz). The optical heterodyne power spectrum for each laser can be seen below in Figures 10 through 15.

Typically, bulk solid state lasers and Er-doped fiber lasers have linewidths of several kHz. With active stabilization of the pump laser even narrower linewidths have been achieved. Semiconductor lasers on the other hand usually have much larger linewidths often in the MHz range. However, semiconductor lasers with optical feedback, such as the DFB lasers characterized in this report, benefit from a reduction in linewidth down into the hundreds of kHz regime. These trends are consistent with the measured values below with the exception of the Planex ECDL from RIO which has a linewidth of just 3.15 kHz, making it a factor of 100 times narrower than the DFB lasers.

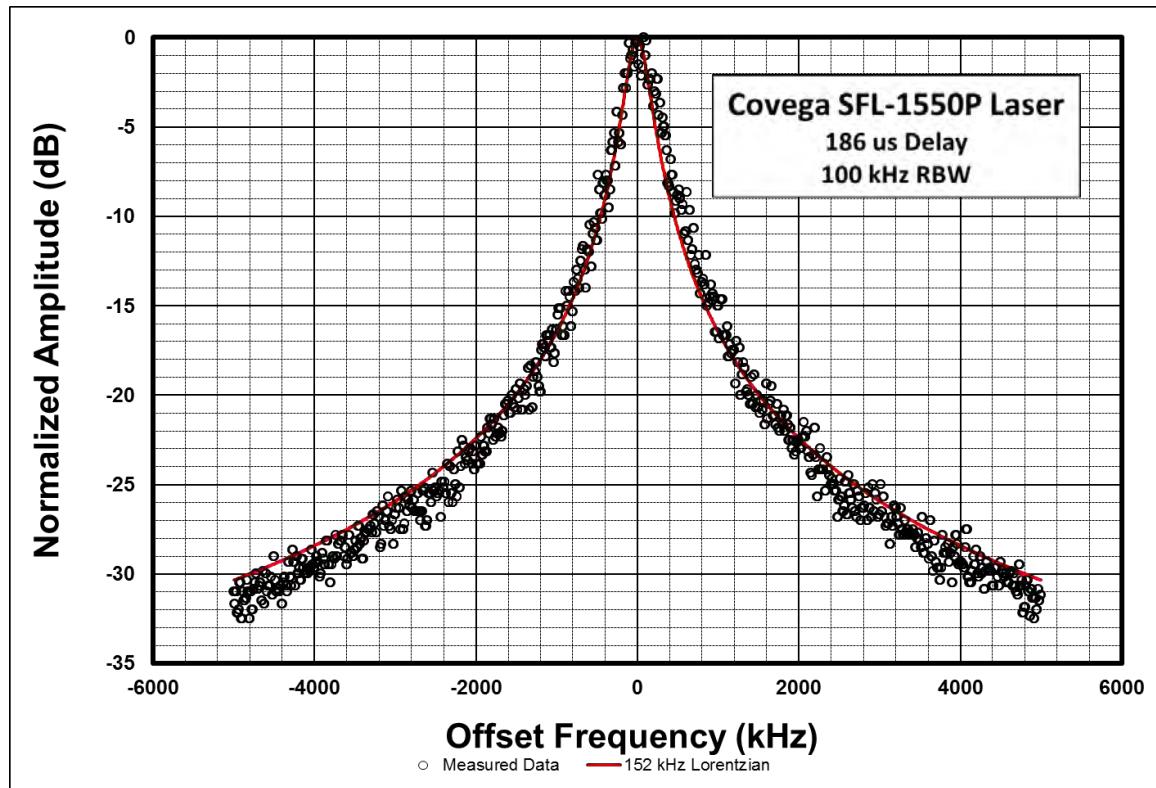


Fig. 10. The measured linewidth spectrum (black) of a Covega SFL-1550P (Serial No. SFL-8321) ECDL. A Lorentzian fit (red) yields a FWHM linewidth of 152 kHz by way of the DSH measurement technique.

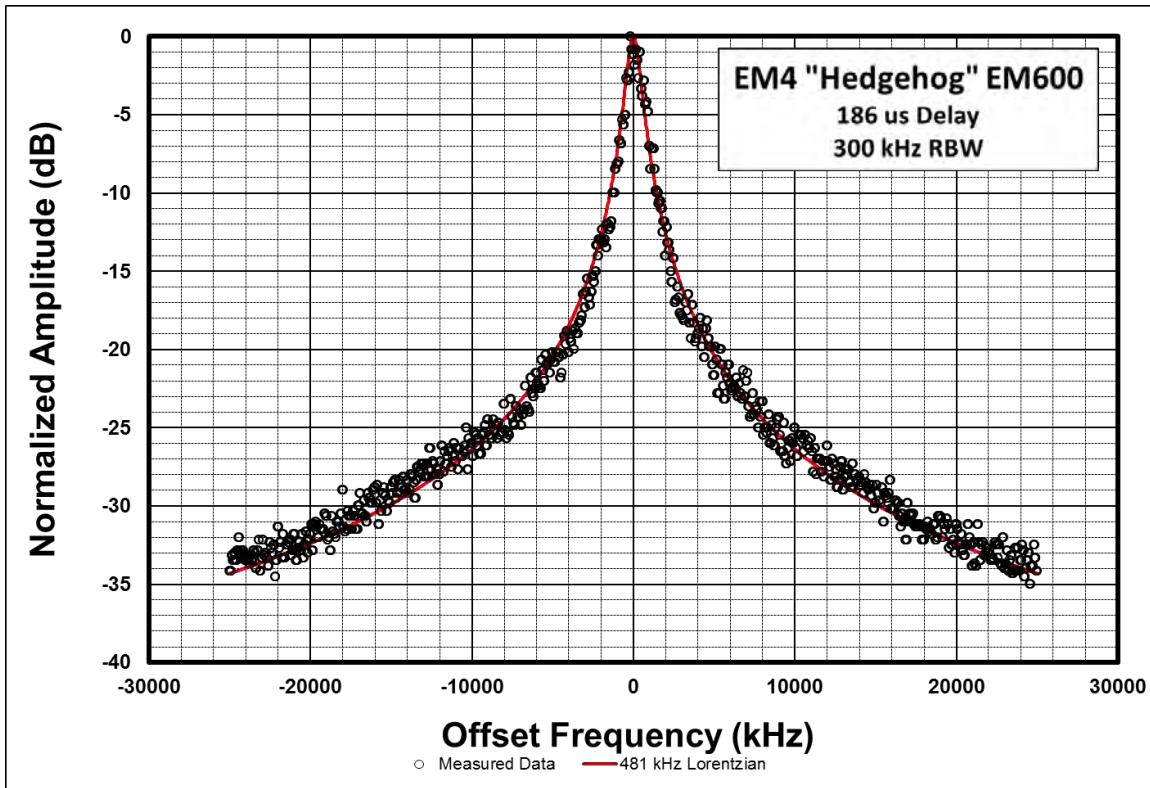


Fig. 11. The measured linewidth spectrum (black) of an EM4 "Hedgehog" E600 (Serial No. E0037572) DFB laser. A Lorentzian fit (red) yields a FWHM linewidth of 481 kHz by way of the DSH measurement technique.

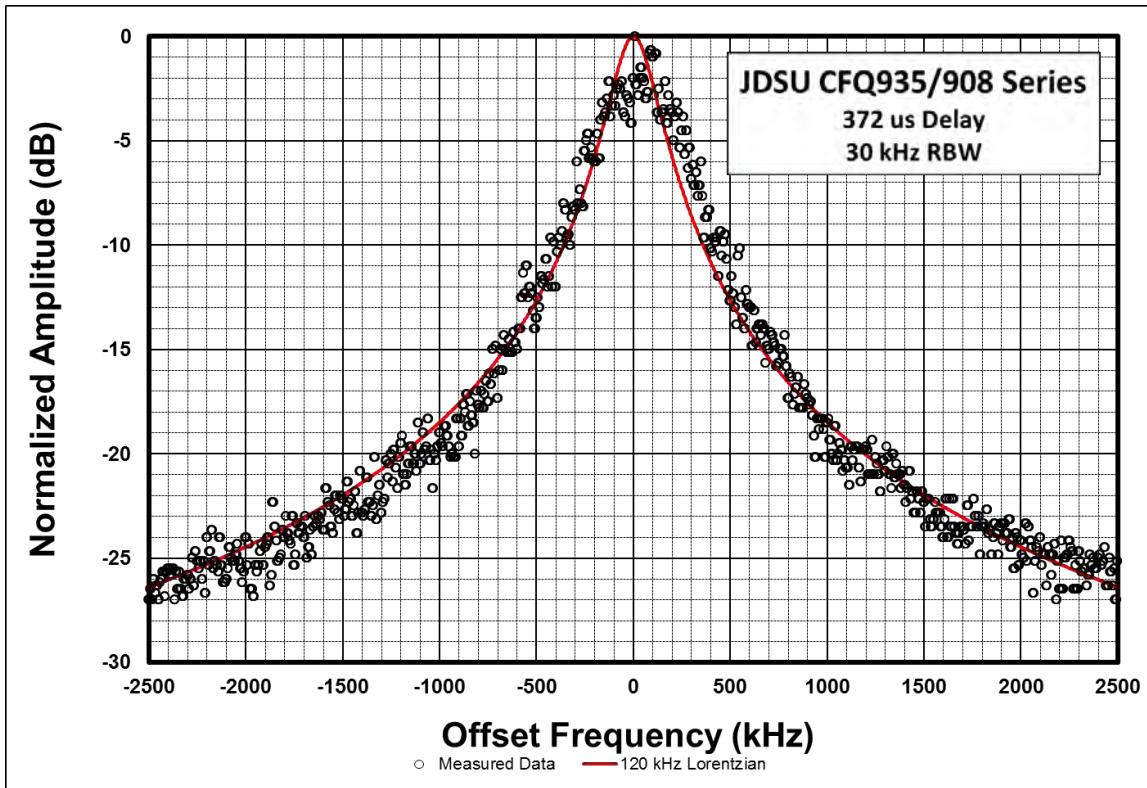


Fig. 12. The measured linewidth spectrum (black) of a JDSU CFQ935/908 Series (Serial No. 804166) DFB laser. A Lorentzian fit (red) yields a FWHM linewidth of 120 kHz by way of the DSH measurement technique.

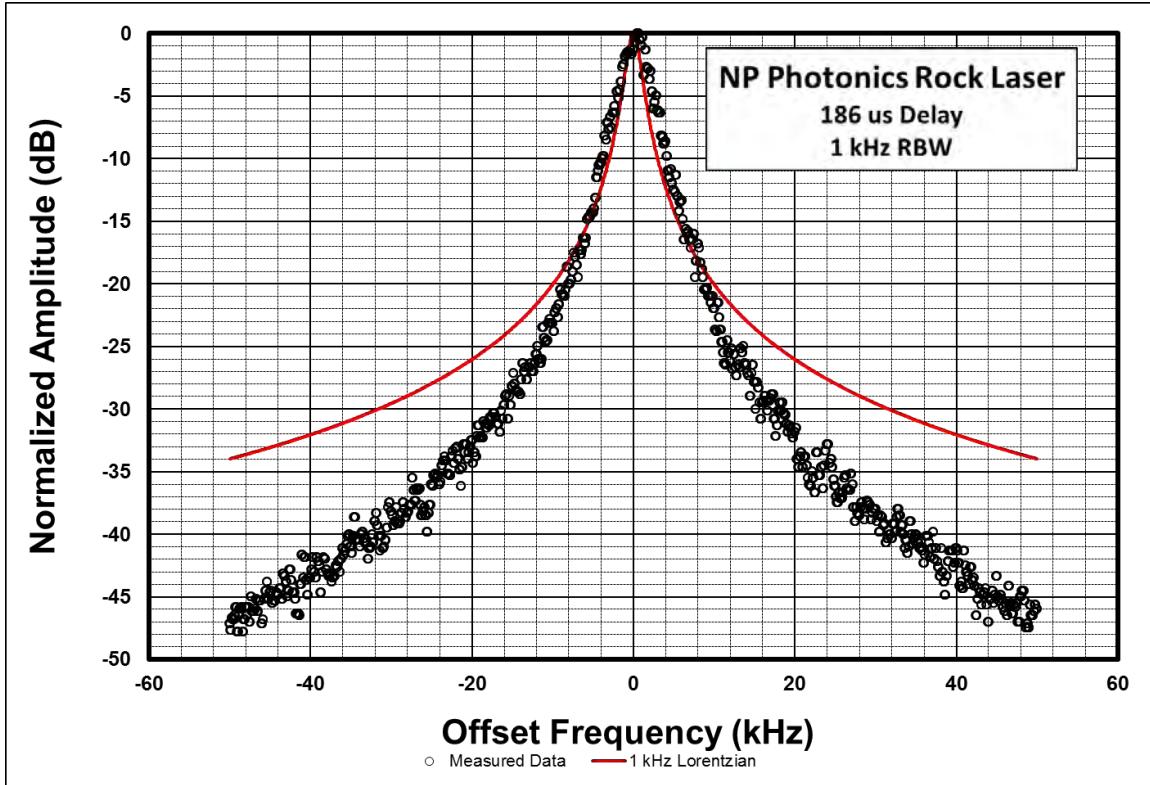


Fig. 13. The measured linewidth spectrum (black) of an NP Photonics “Rock”  $\text{Er}^{3+}$  fiber laser. A Lorentzian fit (red) yields a FWHM linewidth of 1 kHz by way of the DSH measurement technique. The laser lineshape as measured is not Lorentzian, Gaussian, or Voigt. This figure shows that it is likely Lorentzian but with some environmental noise added. The environmental noise sources were likely introduced through a portion of fiber from the measurement setup that was not protected inside the Sorbothane®-lined isolation enclosure. This unprotected section of fiber was susceptible to lab-generated acoustic noise, mechanical vibrations, and temperature gradients.

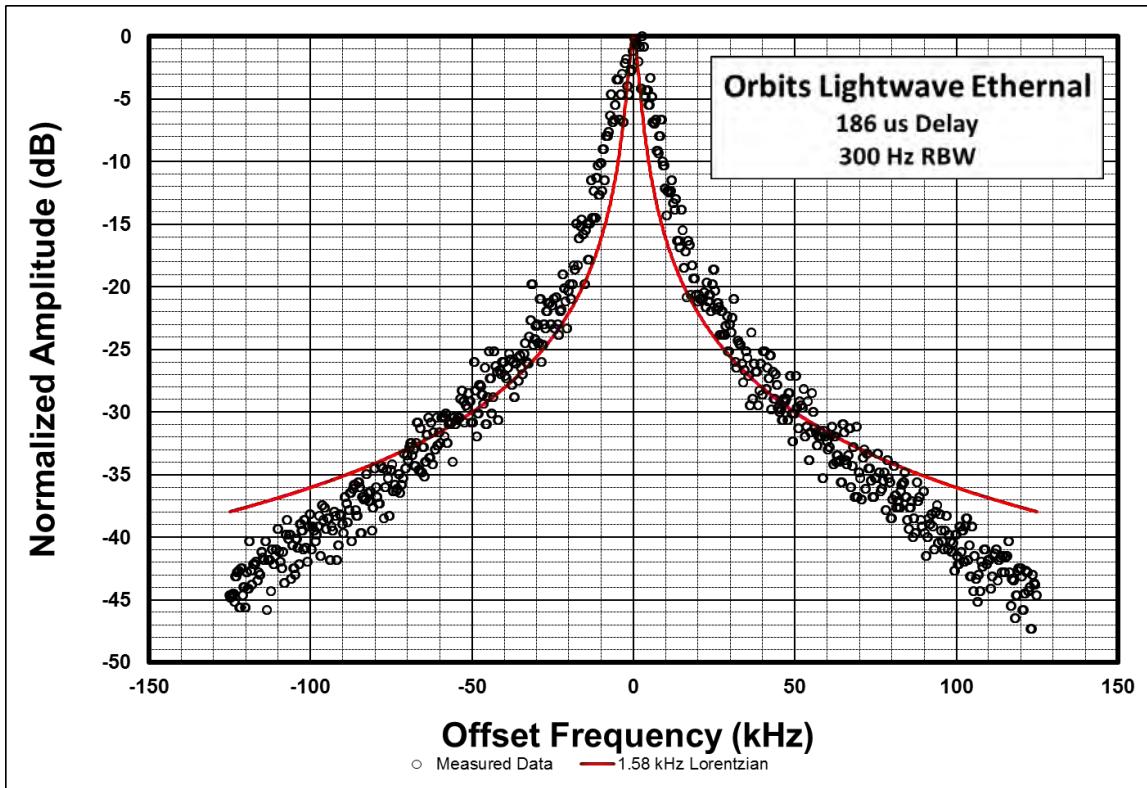


Fig. 14. The measured linewidth spectrum (black) of an Orbits Lightwave “Eternal”  $\text{Er}^{3+}$  fiber laser. A Lorentzian fit (red) yields a FWHM linewidth of 1.58 kHz by way of the DSH measurement technique.

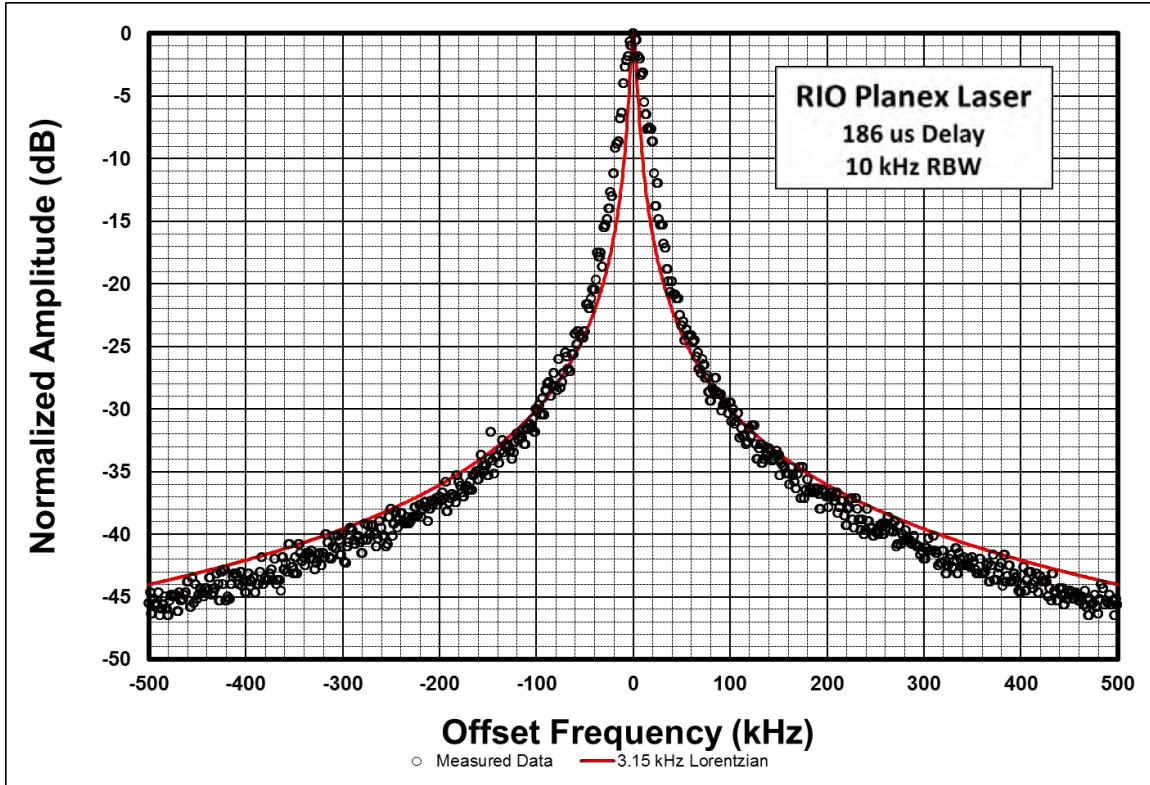


Fig. 15. The measured linewidth spectrum (black) of a RIO Planex ECDL. A Lorentzian fit (red) yields a FWHM linewidth of 3.15 kHz by way of the DSH measurement technique.

## 6 LASER OPTICAL SPECTRA

In this section, the measured optical spectrum of each laser is presented in graphical form. As previously discussed in section 3, an OSA was employed to make this measurement. The normalized optical spectrum for each laser can be seen below in Figures 16 through 22.

All of the lasers covered in this report were able to achieve a SMSR of greater than 50 dB with the exception of the Covega SFL-1550P. With a slight adjustment in drive current (from 290 to 300 mA), the laser from Covega could have its SMSR reduced to  $<3$  dB. The manufacturer's datasheet notes that each SFL-1550P laser has a unique set of temperatures and drive currents that could produce multi-frequency operation. This point could prove to be problematic in fielded applications that experience large temperature excursion from the set point of the laser. It should be noted, to a much lesser degree, the SMSR of the RIO laser was also affected by this same effect.

The optical spectrum of the DFB lasers resembles that of a Fabry-Perot laser but with a greater SMSR. The bulk solid-state Nd:YAG, Er-doped fiber lasers, and the ECDL from RIO are essentially absent of side modes as evident in the figures seen below.

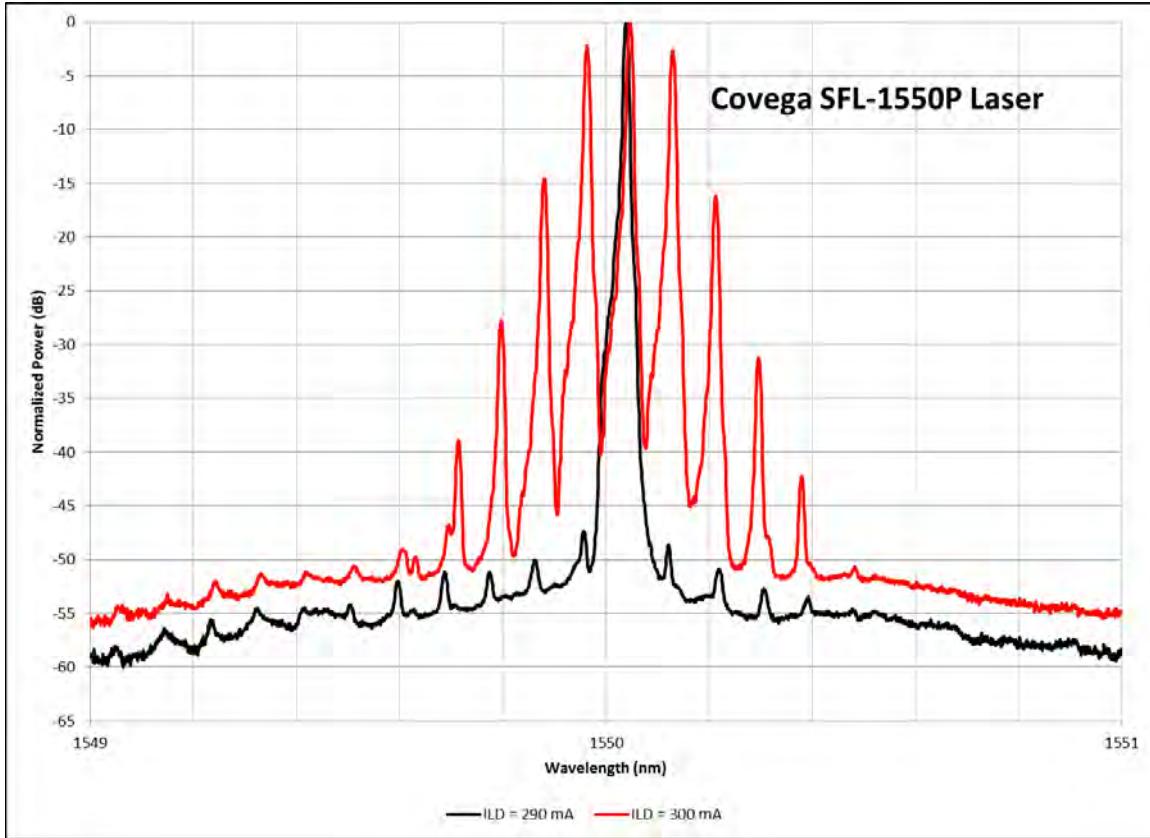


Fig. 16. The measured optical spectra of a Covega SFL-1550P (Serial No. SFL-8321) ECDL at drive currents of 290 mA (black) and 300 mA (red). Clearly, a change in drive current can lead to an increase in the intensity of the side modes. The longitudinal spacing seen here is approximately 10 GHz which results in a corresponding RIN peak as seen above in Figure 3.

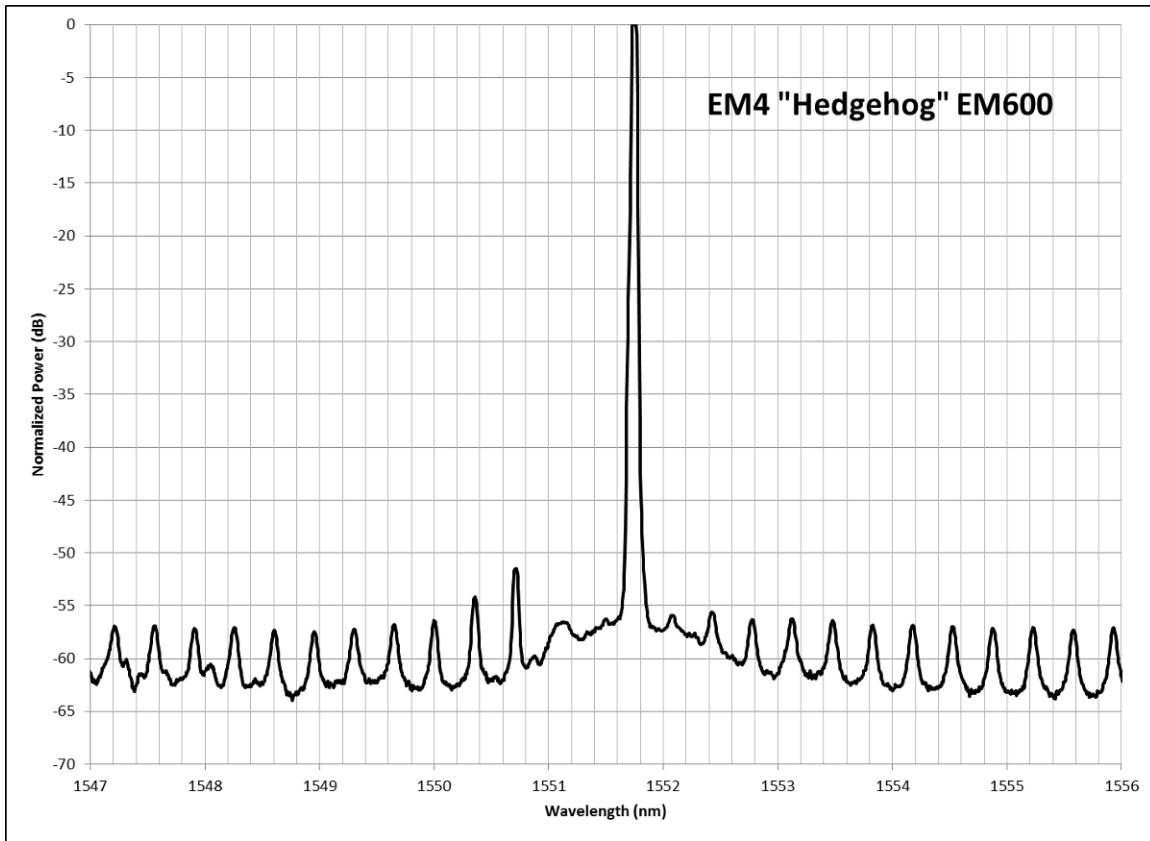


Fig. 17. The measured optical spectrum of an EM4 "Hedgehog" E600 (Serial No. E0037572) DFB laser with the factory set drive current. The longitudinal mode spacing seen here is approximately 43.4 GHz. It can also be seen that the SMSR is >50 dB.

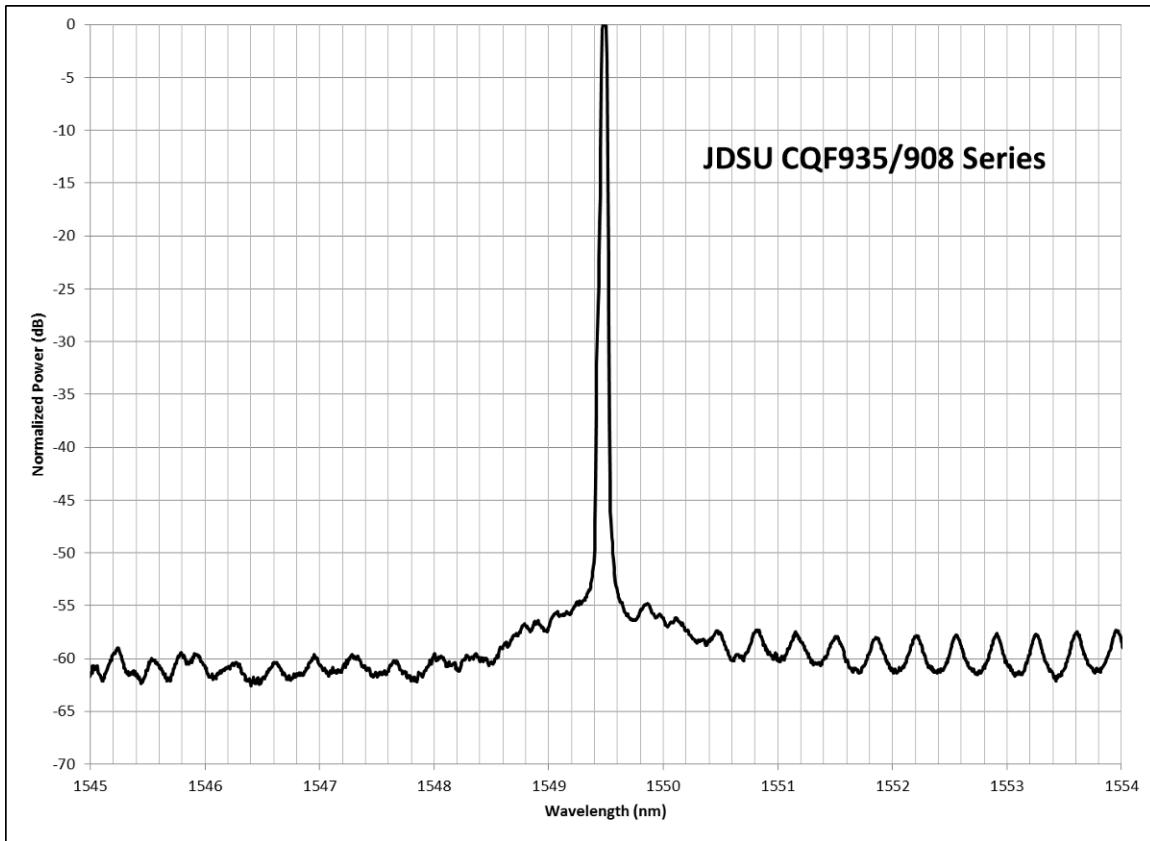


Fig. 18. The measured optical spectrum of a JDSU CFQ935/908 Series (Serial No. 804166) DFB laser with a drive current of 302 mA. The longitudinal mode spacing of 43.6 GHz can clearly be seen in this OSA scan. It can also be seen that the SMSR is >55 dB.

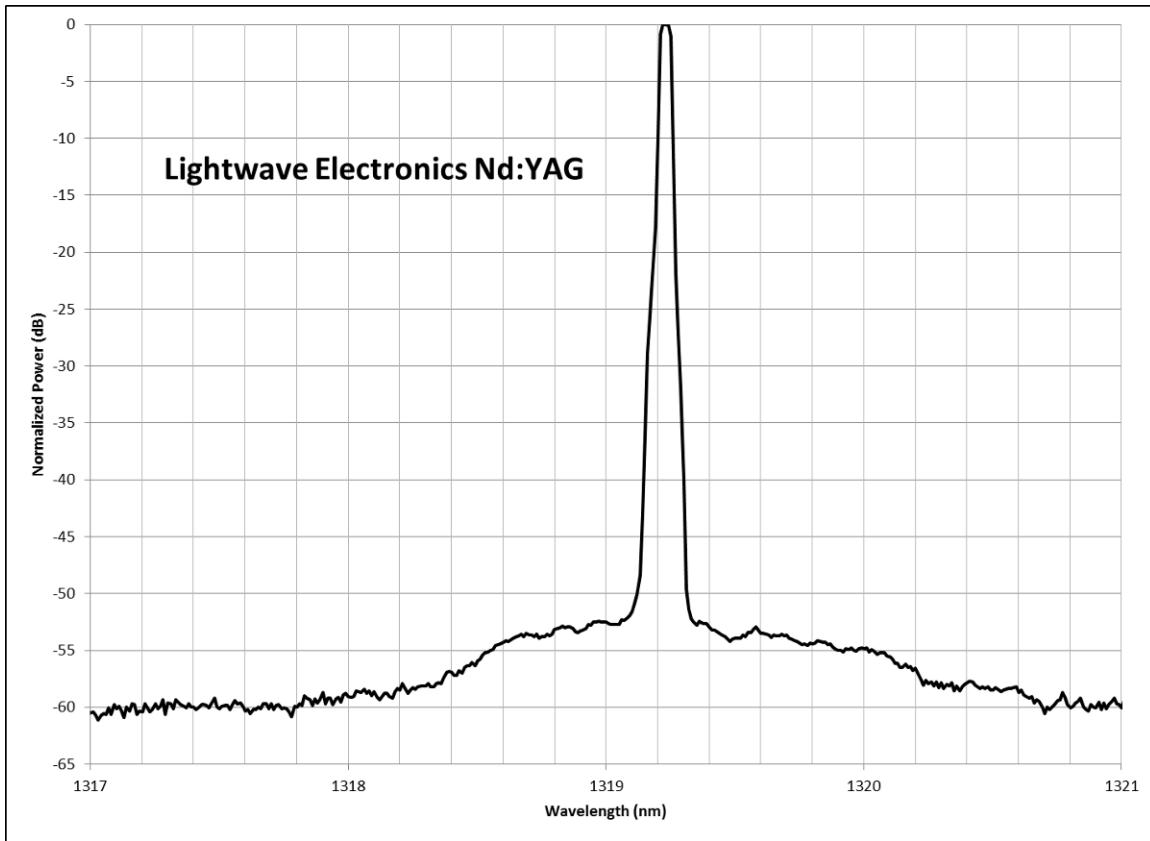


Fig. 19. The measured optical spectrum of a Lightwave Electronics (Serial No. 408) Nd:YAG laser with a total operating current (including the thermoelectric cooler) of 1920 mA. It can also be seen that the SMSR is >50 dB. While there is a pedestal at the base of the peak, no additional longitudinal modes can be seen in this plot.

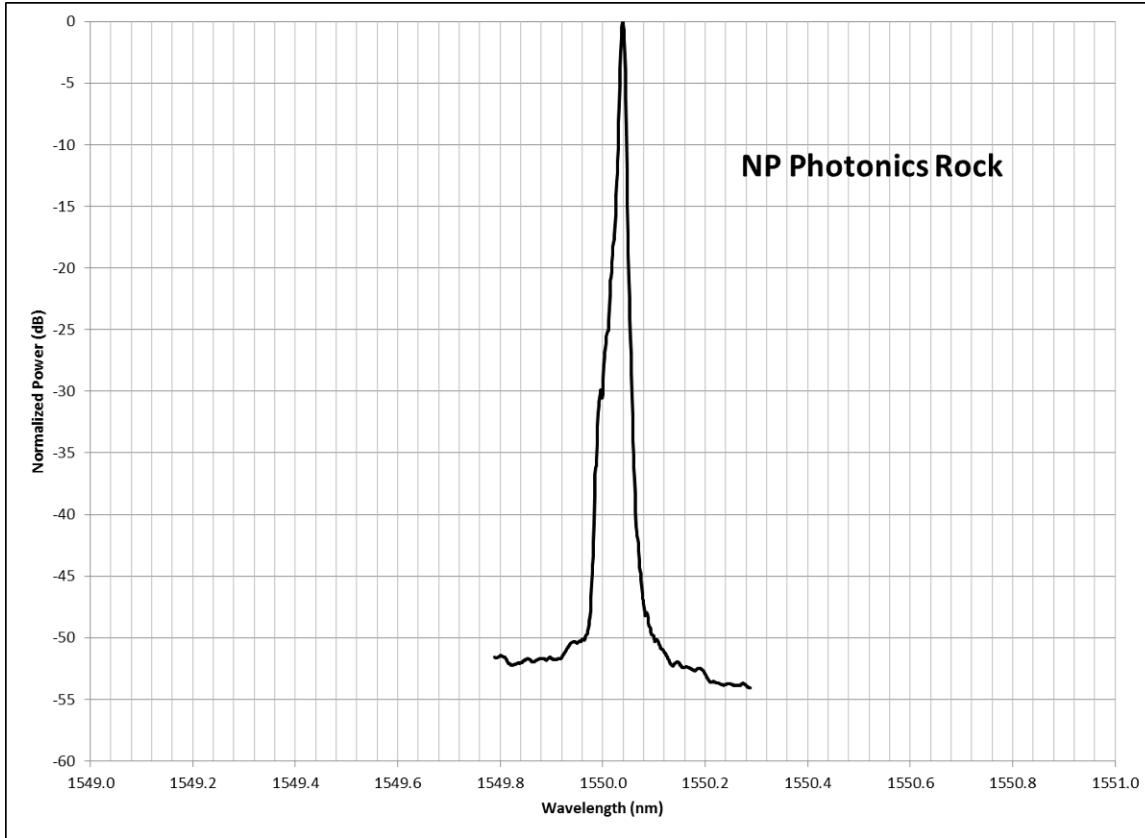


Fig. 20. The measured optical spectrum of an NP Photonics “Rock”  $\text{Er}^{3+}$  fiber laser with the factory-set drive current. It can be seen that the SMSR is  $>50$  dB. With an OSA resolution of 10 pm, some features close to the main peak may not be resolved as seen in the RIN plot (Figure 7) near 2.5 GHz.

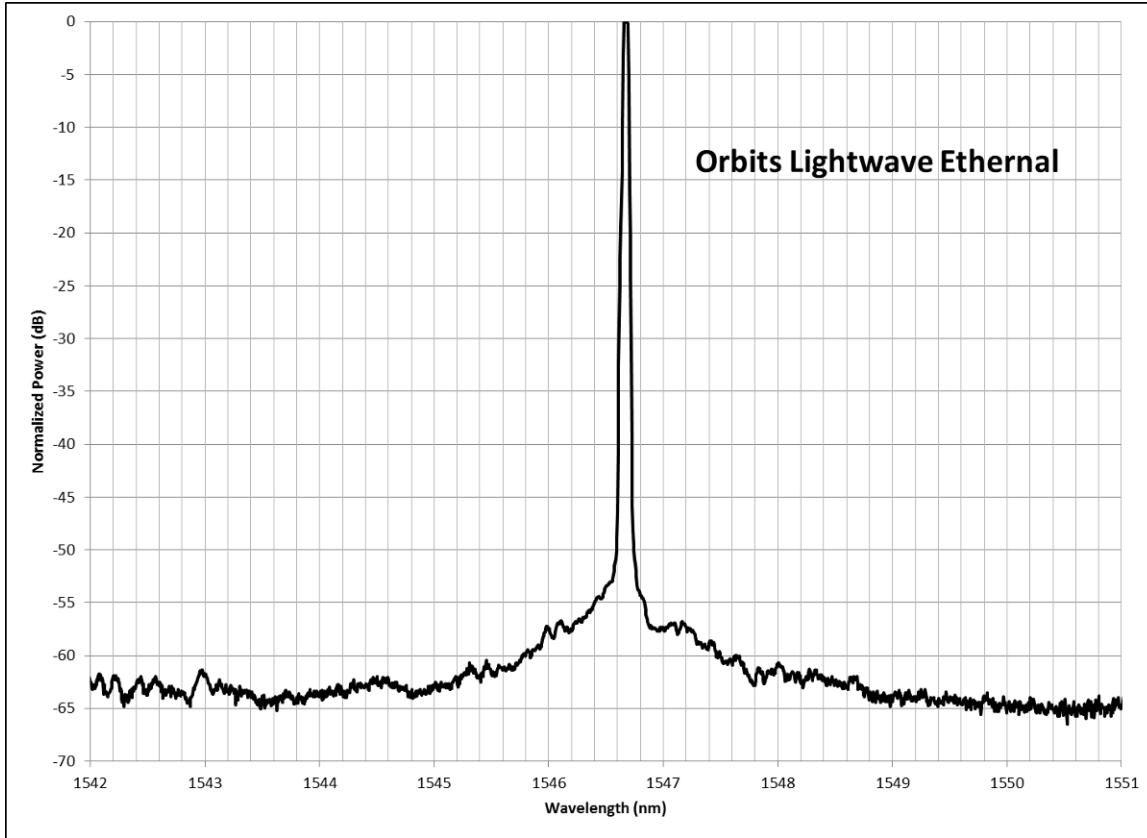


Fig. 21. The measured optical spectrum of an Orbits Lightwave “Ethernal”  $\text{Er}^{3+}$  fiber laser with the factory-set drive current. It can be seen below that the SMSR is  $>55$  dB. With an OSA resolution of 10 pm, some features close to the main peak may not be resolved as seen in the RIN plot (Figure 8) near 1 GHz.

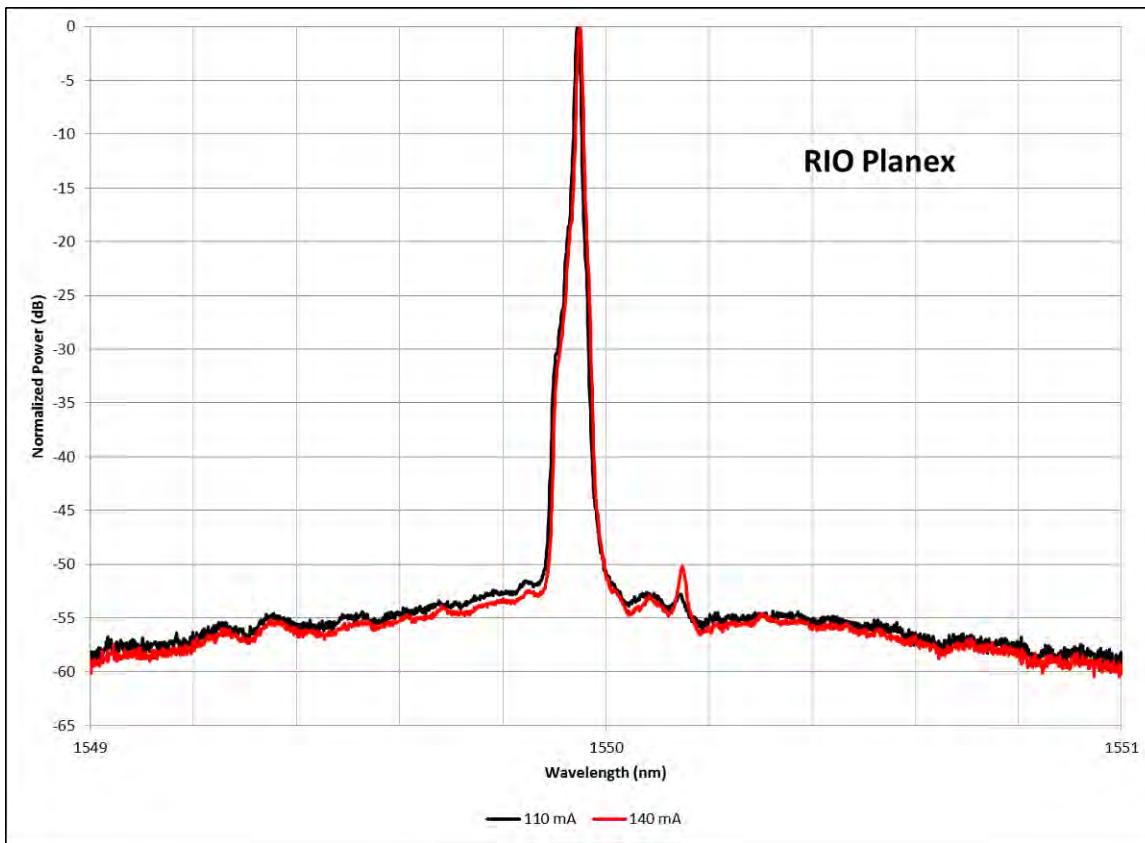


Fig. 22. The measured optical spectra of a RIO Planex fiber laser at drive currents of 110 mA (black) and 140 mA (red). It can also be seen that the SMSR is >50 dB.

## 7 SUMMARY AND CONCLUSIONS

The performance of a series of single-frequency lasers was cataloged in this report. The methodology used to measure the RIN, linewidth, and optical spectrum of each laser was outlined and the results presented. In addition, the different architectures of each laser manufacturer were discussed and the advantages of each approach were commented on.

Because no one laser will simultaneously satisfy all of the major performance metrics of an analog photonic link system, priorities must be set by system designers so that a laser solution can be realized for a particular application. Compromises will need to be made and options weighed. When a compromise cannot be made and no laser exists to adequately satisfy all design goals simultaneously it might be possible to work with the vendor who demonstrates the most promise for that specific application.

For links designed to operate in the MHz range, that are not phase sensitive, an ECDL or DFB laser would be appropriate to consider due to their relatively low intensity noise at those frequencies. However, links transferring signals that are modulated in the GHz range, would benefit from the Er:doped fiber lasers, and if space permitted, the Nd:YAG system. No laser should be selected based solely on this one parameter alone. Obviously, other factors need to be taken into account first.

Such other factors can be output power, linewidth, and SWaP. These factors are generally opposed for the lasers enclosed in this report. The fiber lasers are larger but provide the greatest output power potential. The ECDL and DFB lasers on the other hand benefit from years of telecom development and therefore have a very compact, and presumably, more rugged package. However, they suffer from relatively low output power. In terms of linewidth, the DPSS, Er:doped fiber, and some ECDLs have a two to three orders of magnitude advantage over the DFBs.

Other single-frequency lasers not included in this survey also show potential for use in analog photonic applications. Through work supported by DARPA and SPAWAR, Princeton Optronics now produces a co-doped Er:Yb fiber laser capable of >350 mW of output power with a linewidth of <1 kHz. The co-doping provides higher gain in a shorter length therefore allowing a more compact device. Another benefit to the co-doping is the reduced sensitivity to pump laser fluctuations which decreases intensity noise. Princeton Optronics also developed patented RIN reduction circuitry that reduces the relaxation oscillation peak by over 50 dB [16]. MIT Lincoln Lab has conducted DARPA-supported work that has resulted in a slab-coupled optical waveguide external cavity laser capable of 370 mW and <1 kHz linewidth. The package size is comparable to Er:doped fiber lasers but they believe it could be reduced by a factor of 2 in a future generation [17].

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